Validation of 3D Structure of the San Francisco Bay Area

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Douglas S. Dreger
University of California, Berkeley, California, 94720
Ph. (510)643-1719; Fax (510)643-5811; dreger@seismo.berkeley.edu

Introduction

A part of the effort to characterize future earthquake hazard in the San Francisco Bay Area is the forecasting of strong ground motions for a suite of earthquake rupture scenarios. This research project supports this effort by testing the validity of proposed 3D velocity models that are used in the ground motion simulations (e.g. Aagaard et al., 2008ab). We have simulated ground motions to 0.5 Hz for 10 small to moderate events for several versions of the USGS 3D velocity model. We have compared the arrival times of both P and S waves, the peak ground velocity (PGV), and the complete waveforms.

Approach

We use an elastic forth-order, staggered grid finite-difference program, e3d, written by Dr. Larsen (Larson and Shultz, 1995) to simulate the complete three-component seismic wavefield of 10 small to moderate events (Table 1, Figure 1). The synthetic seismograms are complete with respect to body and surface waves, as well as far- and near-field terms. For each event we assumed the source focal parameters reported in the Berkeley Seismological Laboratory (BSL) moment tensor catalog.

Table 1: Event Data

ID	Date	lon	lat	Strike	Dip	Rake	Depth	Moment	Mw
gilr93016	01/16/1993	-121.455	37.028	331	83	166	7	2.40E+23	4.9
boli99230	08/18/1999	-122.686	37.907	115	49	69	8	7.25E+22	4.5
napa00247	09/03/2000	-122.414	38.377	60	75	18	11	3.74E+23	5
gilr02134	05/14/2002	-121.6	36.967	212	87	-6	8	2.86E+23	4.9
dubl03033	02/02/2003	-121.937	37.74	67	88	-19	14	1.36E+22	4.1
smar06166	06/15/2006	-121.492	37.102	360	78	-152	5	4.18E+22	4.4
glen06215	08/03/2006	-122.589	38.363	256	86	19	5	5.64E+22	4.4
lafe07061	03/02/2007	-122.098	37.901	82	89	-1	14	2.77E+22	4.2
oakl07202	07/20/2007	-122.18	37.8	321	89	168	5	2.52E+22	4.2
alum07251	10/31/2007	-121.776	37.4323	323	87	180	11	1.85E+24	5.4

The simulations were performed on a 64-cpu Xenon cluster at the BSL. This system allows the consideration of problems that span geographically the greater San Francisco bay area to a maximum frequency of 0.5 Hz. Although the USGS velocity models that we used have shear wave velocity in places lower than 500 m/s we had to cap the minimum shear wave velocity to

500 m/s for computations to be tractable on this computer system. The model discretization is 125m, and for 8 grid points per minimum wave-length, to avoid grid dispersion effects, the maximum frequency for a minimum shear wave velocity of 500 m/s is 0.5 Hz.

The approach that we have taken is to simulate three-component velocity records at stations of the Berkeley Digital Seismic Network, the CGS strong motion network, and USGS strong motion sites. The simulated seismograms are compared to the observations in three primary ways. First we use waveform cross correlation to determine P-wave and S-wave arrival delays. Second, we compare observed and simulated peak ground velocity (PGV), where both the observations and synthetic time histories were low pass filtered at 0.5 Hz using a 4-pole, acausal Butterworth filter. Finally, the waveforms are compared. For both the PGV and waveform comparisons we examine the ability of the velocity model predict observations in three different passbands, namely 0.033 to 0.15 Hz, 0.1 to 0.25 Hz, and 0.1 to 0.5 Hz.

We simulated motions for two 3D velocity models developed by the USGS, namely model 5.1.0 and 8.3.0 (e.g. Brocher et al., 1997; Brocher, 2005; Brocher et al., 2006; Jachens et al., 1997; Jachens et al., 2006). Model 8.3.0 reduced seismic wave velocities in the upper crust to reduce traveltime mismatches observed by Rodgers et al. (2007). In Figure 2 we compare the two models by differencing the reported velocity in each 125m grid layer. The plot shows the percent change, where positive values indicate a faster model 5.1.0 compared to model 8.3.0. The mean velocity of each layer is reduced by approximately 5% in the depth range from 5 to 30 km in model 8.3.0. The error bars show the variation of the difference function indicating that locally in the model there are significant differences between -17 to 20% in the shallowest layer, to 0 to 15% in the upper crust ranging from 5 to 17 km depth. These fluctuations represent changes to both the seismic velocity and the 3D structure (depth of interfaces, etc.) since we simply computed the average for each depth slice. Nevertheless, it does show that on average model 8.3.0 is about 5% slower than model 5.1.0.

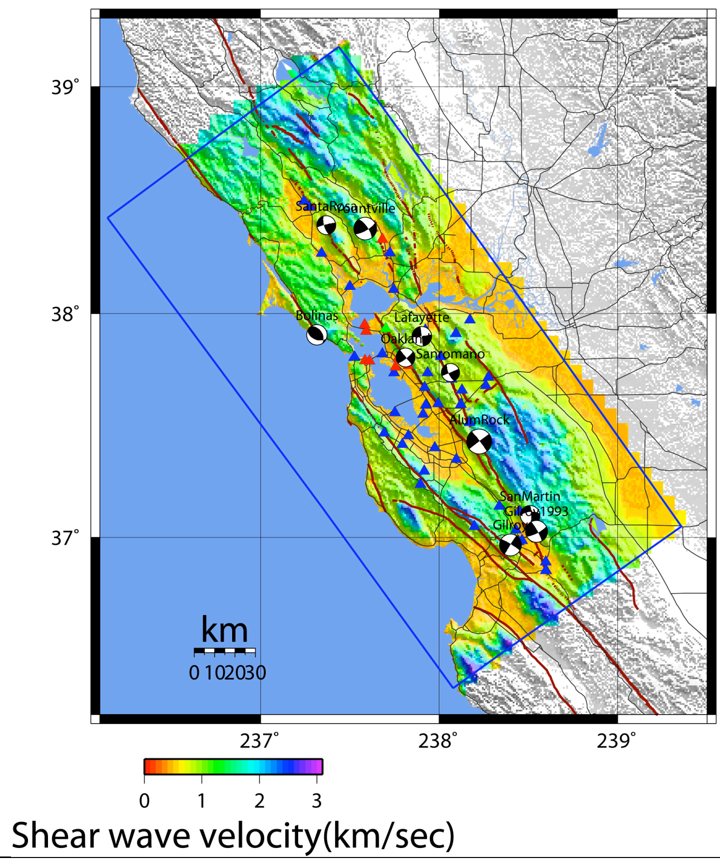

Figure 1. Map showing the SF06 3D (model 5.1.0) velocity model capped at 500 m/s and focal mechanisms for the 10 simulated events.

Figure 3 compares PGV maps for two earthquakes, namely the 2002 Mw4.9 Gilroy (gilr02134, Table 1) and the 1999 Mw4.6 Bolinas (boli99230, Table 1) earthquakes. The vector maximum PGV is plotted for each event for both the 5.1.0 and 8.3.0 3D velocity models. The effects of 3D structure are seen clearly in elevated PGV within the regions depositional basins, and the distribution of PGV in the two models is similar. Both events show relatively larger motions in the river valleys (Cotati, Sonoma and Napa) north of San Pablo Bay, although the proximity of the Bolinas earthquake to these structures results in the basin generated waves being more strongly excited. The basin amplification is approximately a factor of 3 to 4 in the models. At greater distances the PGV in model 8.3.0 is seen to decrease slightly, however as will be shown later the model matches the observed motions quite well.

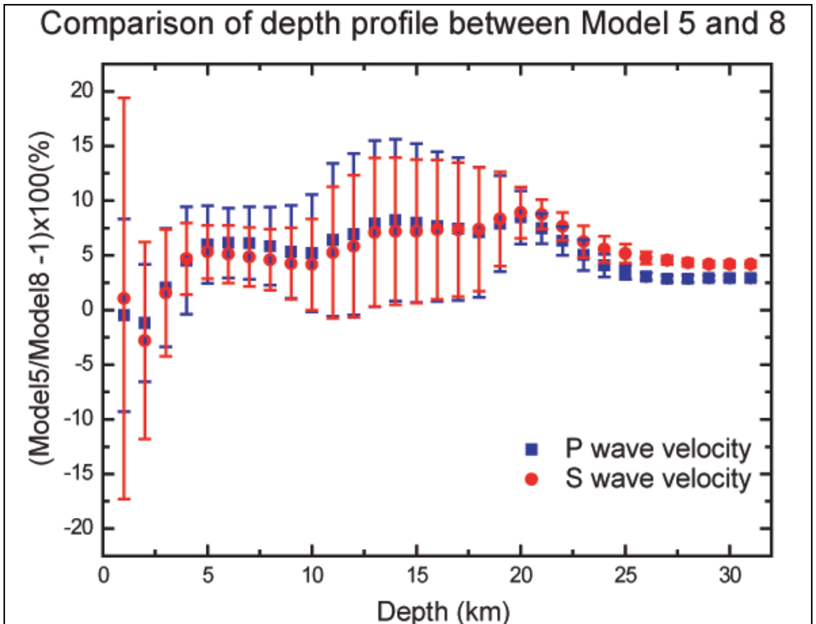

Figure 2. Comparison of P and S wave velocity in the USGS version 5.10 and 8.3.0 3D velocity models. Positive percentage values indicate model 5.1.0 is faster than model 8.3.0

Results

We have compared the simulated records with observations of P-wave arrival times, peak ground velocity (PGV), and in terms of complete waveforms. Rodgers et al. (2007) reported that model 5.1.0 produced synthetic seismograms where S-waves and surface waves arrived early. We performed an analysis of P-wave arrival times by using cross-correlation to determine arrival time differences. For this analysis we low pass filtered the velocity records using an acausal Butterworth filter with corners of 0.1 and 0.5 Hz, and then used a waveform cross-correlation to find the relative arrival times. As Figure 4 shows, consistent with Rodgers et al. (2007) for S-wave arrival times, the P-wave arrival times for model 5.1.0 are systematically early. The arrival time difference increases with distance suggesting it is a systematic error in the seismic wave speed, where the P-wave velocity is too high. A recalculation using model 8.3.0 shows that the simulated arrivals are still a little early, but that most of the disagreement with the observations has been accounted for.

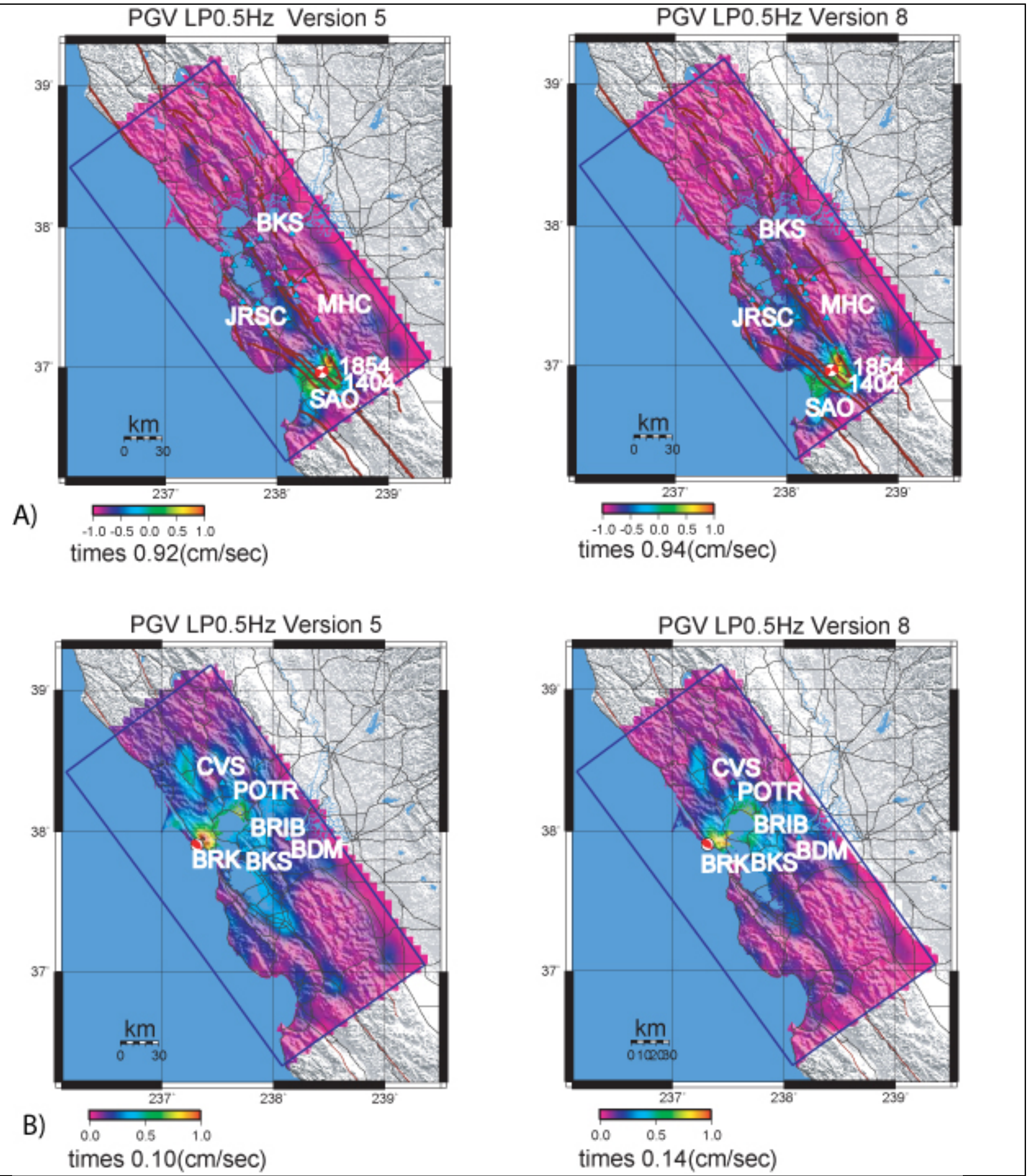

Figure 3. A) Comparison of PGV for the 2002 Gilroy earthquake for the two 3D velocity models. B) Comparison of PGV for the 1999 Bolinas earthquake for the two 3D velocity models.

The comparison of PGV for both models 5.1.0 and 8.3.0 reveals that both 3D models predict the observed PGV well (Figure 5). The comparison shown is for over 4 orders of magnitude to values exceeding 1 cm/s where damage begins to manifest in weak unreinforced structures. In the low frequency band (0.03 to 0.15 Hz) all of the small events are essentially point-sources and we see that there is very good one-to-one correspondence between observed and simulated PGV. Both models perform well, but model 8.3.0 seems to reduce the dispersion slightly. This is also true of the intermediate passband (0.1 to 0.25 Hz). At higher frequencies the correlation remains good, however unaccounted for source effects for the larger events, and 3D wave propagation and site conditions become more important leading to higher dispersion in the predicted amplitudes. Since PGV behaves linearly in large events, and results from waves of 1 to several seconds period for events larger than M6, well within the range of the passband of our simulations, the comparison strongly suggests that both models, and particularly model 8.3.0 is suitable for simulating strong ground motion scenarios for the region's high risk faults. It is noted however that the comparison in Figure 5 is log-log, and that the dispersion represents a factor of 2 to 4 in simulated motions. This fact should be considered in the predictive maps of scenario earthquake simulations. Finally, for the largest event considered, the 2007 Mw5.4 Alum Rock earthquake there can be significant differences in simulated PGV depending upon the assumed duration of the source, 1.5 or 2.0 seconds for model 5.1.0 simulations, or whether a point-source or finite-source model is used for the 8.3.0 simulations (Figure 5).

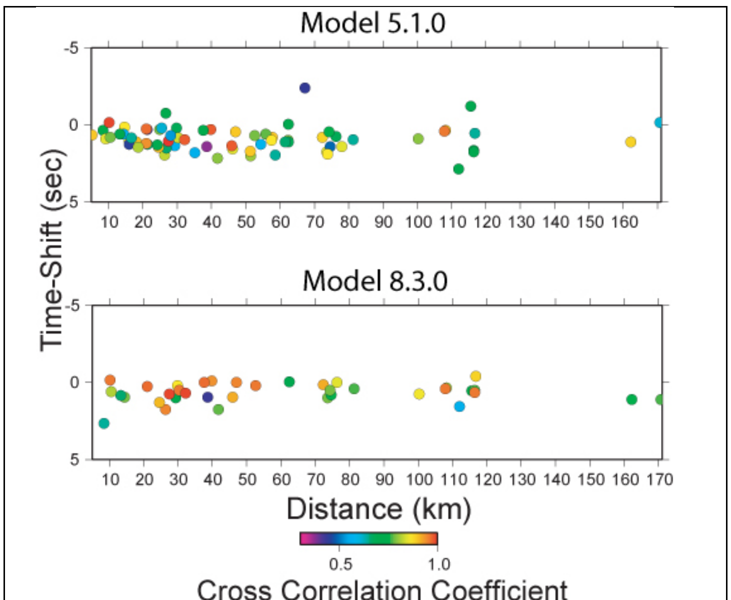

Figure 4. Top shows the relative time shift between synthetic and observed P-waves for model 5.1.0. Positive time shift means the synthetic is early and the model is fast. The color scale shows the level of cross-correlation of the synthetic and observed P waveforms. The bottom shows the same for model 8.3.0.

All though the PGV is relatively well explained, and in many cases the three-component waveforms match that data well there remain paths that could benefit from model refinement. In Figure 6 three component waveforms for the Bolinas earthquake are compared and in all cases, except the paths to BDM and POTR the fit is good. The paths to POTR and BDM are in the same general eastward direction yet while the fit to the simpler BDM records is ok, there is significant mismatch at POTR indicating unmodeled structure north of delta, and possibly in San Pablo Bay. In Figure 7 for the 2002 Gilroy earthquake the two closest stations have fair agreement to the primary S waveforms, but the model fails to explain the large secondary surface wave train at station 1404, which is due to sediments in the Hollister and Salinas valleys. While the synthetics explain PGV at sites 1404 and 1854 within a factor of less than 2, they significantly under predict the duration of strong shaking. There are other examples of very good to excellent waveform agreement as well as paths that could use additional waveform modeling and model calibration.

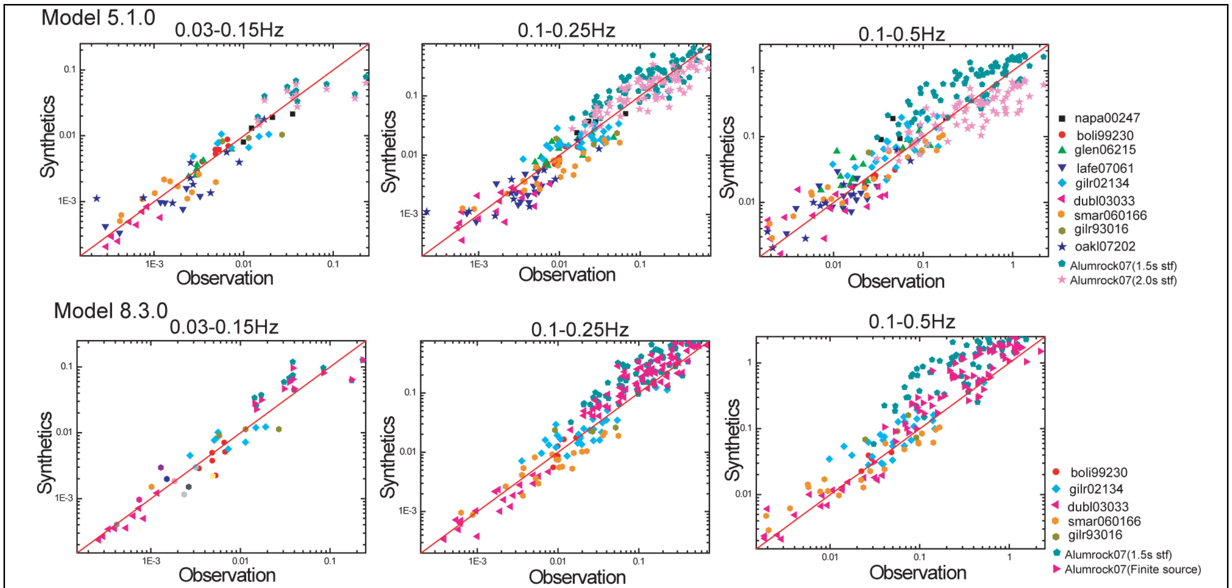

Figure 5. Top row shows the comparison between observed and synthetic PGV in three passbands, 0.03-0.15, 0.1-0.25, 0.1-0.5 Hz for model 5.1.0. The bottom row shows the same for model 8.3.0. The symbols are for different simulated events. The corresponding legends are to the right.

The results presented in this report are for elastic calculations that do not account for intrinsic attenuation. We have also performed simulations taking into account intrinsic attenuation using values of Q provided in model 8.3.0. These simulations show little effect on waveforms or amplitudes because of the short source-receiver paths, and relatively low frequency passband ($f < 0.5$ Hz) that we studied. The effects of Q would clearly be important in the simulation of PGA and for much longer source-receiver paths.

Conclusions

We have simulated complete, three-component waveforms for 10 small to moderate earthquakes, which have occurred throughout the greater San Francisco Bay Area. Two 3D models, model 5.1.0 and 8.3.0, constructed by the USGS (Brocher et al., 1997; Brocher, 2005; Brocher et al., 2006; Jachens et al., 1997; Jachens et al., 2006) were tested in the simulations. We find that the updated model 8.3.0 performs well in explaining the timing of both P- and S-wave groups, and in explaining PGV to a frequency of 0.5 Hz. Since earthquakes larger than M6 have PGV carried by waves of 1 to several seconds period, the results we have obtained in this same passband for smaller earthquakes indicate that the 3D model is suitable for the simulation of PGV to assess the strong shaking hazard of future earthquakes. It is important to recognize however that while there is good correlation between simulated and observed PGV the level of dispersion observed in log space corresponds to a factor of 2-4 variance in the simulated motions. This fact should be considered in the interpretation of simulated PGV for scenario earthquakes. We have examined peak ground acceleration (PGA) in these same passbands and also found good agreement between synthetic and observed. In contrast to PGV, PGA in actual recordings is carried by higher frequency waves of several to 10s of Hz, and the 3D velocity model remains untested in this passband for these small to moderate sized events. Finally, the inspection of waveform fits for specific source-receiver paths show that synthetic waveforms can either match well or very poorly indicating that more velocity model refinement is needed to explain the details of the seismic wave propagation, and while PGV may be well matched the durations could be under estimated.

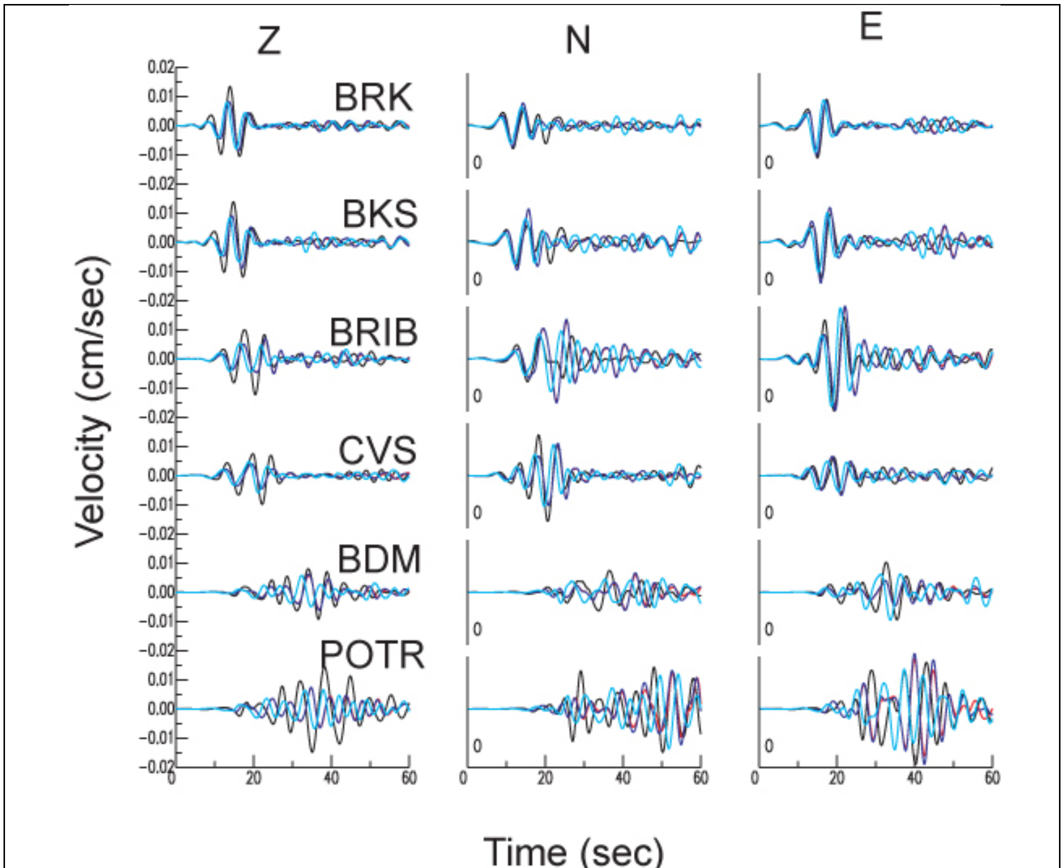

Figure 6. Three-component velocity waveforms (black) for the 1999 Bolinas earthquake are compared to synthetics for models 5.1.0 (blue) and 8.3.0 (red). The data and synthetics have been bandpass filtered between 0.10 to 0.25 Hz. See Figure 3b for the locations of the event and the stations.

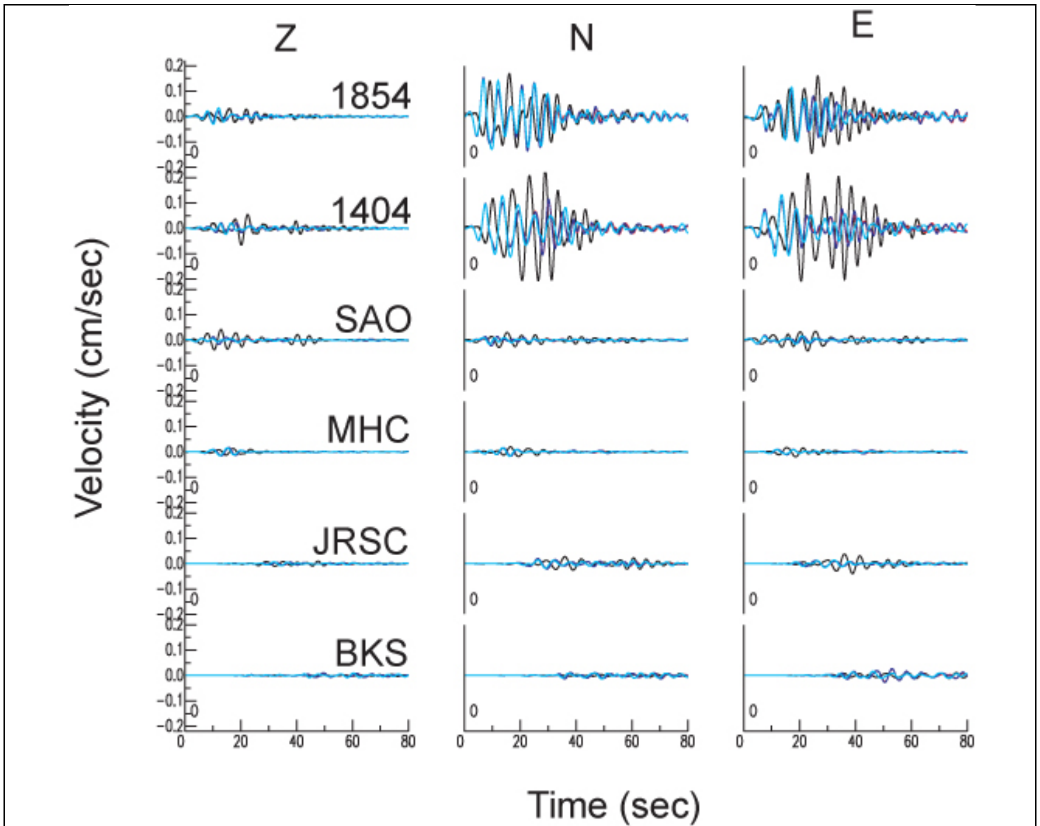

Figure 7. Three-component velocity waveforms (black) for the 2002 Gilroy earthquake are compared to synthetics for models 5.1.0 (blue) and 8.3.0 (red). The data and synthetics have been bandpass filtered between 0.10 to 0.25 Hz. See Figure 3a for the locations of the event and the stations.

Peer-Reviewed Reporting of Results

We are presently preparing a manuscript for submission to Geophysical Research Letters that describes the PGV modeling results described in this report.

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